

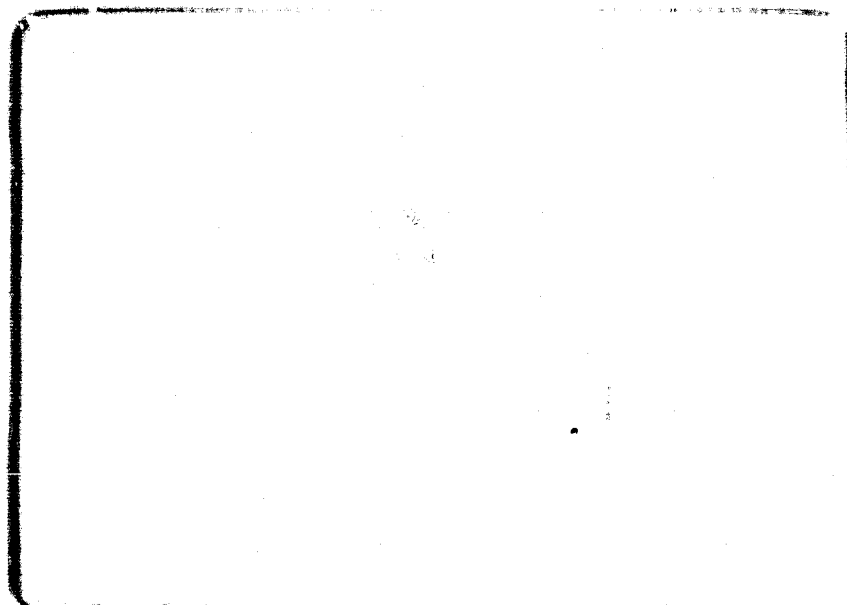
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FAST POLARIZATION CHANGES IN MM-MICROWAVES EMISSION OF WEAK
MULTISTRUCTURED SOLAR BURSTS

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ABSTRACT

Circular polarization of weak multi-structured solar bursts was measured at mm-microwaves (22 GHz, $\lambda = 13.5$ mm) with unprecedented sensitivity (0.03 sfu rms) and high time resolution (1ms). It was shown for the first time that sudden changes occur in the degree of polarization with time scales of 0.04-0.3 s. In most cases the degree of polarization attained maximum values before the maximum flux in both mm-microwaves and hard X-rays with time scales of 0.04-1.0 s. The timing accuracy in determining the degree of polarization was 40ms.

Physical phenomena are discussed invoking one or a combination of various possible causes for the observed effects. The bursts at mm-microwaves were weak compared to the contribution of the pre-existing active regions, and therefore the changes in magneto-ionic propagation conditions for emerging radiation may play an important role in the observed effects. We also discuss composite effects due to more than one polarizing mechanism or more than one polarized spots within the antenna beam. The observed fast polarization changes may ultimately be related to the primary magnetic transients which are believed to initiate the bursts. The time scales suggest that energy release rates in time structures of small bursts are comparable to rates usually attributed to large bursts (i.e., 10^{28} erg s⁻¹).

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1. INTRODUCTION

Radio emissions from solar active regions, and from the bursts occurring in them, are known to be polarized. Referring first to single dish observations at centimeter microwaves, only the circular component of polarization has been identified (Akabane 1958; Magun and Mätzler, 1973). The polarization is usually attributed primarily to the propagation of radio waves in an optically thin plasma in the presence of a magnetic field. Equations describing the radio propagation in such media are well established (for example Kakinuma and Swarup, 1962; Kundu, 1965; Zheleznyakov, 1970). Several authors have used these equations to determine the magnetic field strengths in non-flaring active regions and to determine time variations in bursts (Gelfreikh, 1962; Kaufmann et al., 1970; Wassenberg, 1971; Basu and Scalise, 1971; Kaufmann and Santos, 1974; Steffen, 1975; Kaufmann, 1978; Bogod and Gelfreikh, 1980). Intrinsic circular polarization arising from gyrosynchrotron emission also can be important (Dulk and Marsh 1981).

Most of the observations made with single antennas have relatively low signal-to-noise and poor time resolution, but they have shown that there are variations in polarization degree not correlated with variations in total flux. Polarization changes tens of seconds prior to major bursts were attributed to large changes in the characteristic scale of the magnetic field at the emitting region (Kaufmann and Santos, 1974). Changes in polarization on similar long time scales were suggested to be the result of the combined polarization of two sources with time varying opposite polarization senses observed by the same antenna beam (Wassenberg, 1971). Faster bursts several seconds in duration observed at cm-microwaves have not shown corresponding polarization changes within the sensitivity attainable by a patrol radio-telescope (Kaufmann, 1978).

The use of large interferometers at cm-microwaves with high sensitivity and spatial resolution, such as the Very Large Array (VLA), Owens Valley Radio Observatory (OVRO), Westerbork

Synthesis Radio Telescope (WSRT), and Nobeyama Solar R Observatory (NSRO) have revealed new aspects of polarized radio active centers and bursts. Dramatic changes in circular polarization extending from a few minutes to an hour before flare eruption were reported (Lang 1980). They are attributed to changes in the magnetic field configuration. It was shown by various authors that, in general, the most intense microwave source during the impulsive phase of a burst is situated at or near the top of a magnetic arch, sometimes extending along the neutral line between the H- α brightenings (Alessandrakis and Kundu 1978; Marsh and Hurford, 1980; Marsh et al. 1980; Kundu 1981). Prior to the burst maximum, however, there were observations of double or multiple polarized structures (Kundu et al. 1974; Lang 1974; Marsh et al. 1980). After burst maximum the microwave source sometimes elongates and eventually splits into two or more oppositely polarized sources, in the apparent direction of the footpoints (Kundu and Vlahos, 1979; Marsh and Hurford, 1980; Kundu, 1981). Multiple spike bursts analysed with the VLA have indicated the presence of several emitting sources suggesting the formation of an arcade of bipolar loops (Kundu, 1981; Kundu et al. 1982a). Another example, however suggests a single source emitting several spikes with a high degree of polarization (Lang et al. 1981).

We should bear in mind, however, that these spatially complex and diversified descriptions are restricted in time resolution. The VLA "snapshots" for example are taken only every 10s. The interferometer at OVRO, however, is capable of a time resolution better than 50 ms. By combining VLA snapshots with OVRO data, it was suggested that, in addition to the major microwave source resolved by the VLA to within a few arc sec, the sources of the individual spikes were unresolved and were distributed over a < 1 arc sec region, spatially distinct from the main burst source (Hurford et al., 1979, 1982).

Interferometric microwave solar burst observations, with a time resolution of 0.8s considerably faster than the VLA "snapshots", were carried out at NSRO (Kai 1980). Kosugi (1980) observed a burst at NSRO made up of highly polarized fast spikes superimposed on a slowly varying and weakly polarized component of the microwave flux. He suggested that fast spikes

were associated with two spot sources and that the slower component was associated with a source having two weak and oppositely polarized elements.

In the present study we concentrate the on flux and polarization changes with time scales shorter than one second. Observations with large single-dish antennas provide the highest time resolution with high sensitivity, two factors of particular importance for the investigation of fast bursts. Although such observations are limited in spatial resolution, they can provide very accurate determinations of the time development of circular polarized components of microwave burst emission. These microwave observations are complemented in several cases by coincident hard X-ray observations with similar high sensitivity and time resolution.

2. OBSERVATIONS AT MM-MICROWAVES AND HARD X-RAYS

In the present study we investigate weak multi-structured bursts with unprecedented accuracy at a mm-wavelength (22 GHz, $\lambda = 13.5$ mm). The sensitivity was 0.03 s.f.u., r.m.s. (1 s.f.u. = 10^{-22} W m⁻² Hz⁻¹), and the time resolution in the right- and left- polarization outputs was 1 ms, i.e., 2-3 orders of magnitude better than a regular solar patrol radio-telescope. Circular polarization degree was determined every 40 ms. These solar observations were made with the 45 ft mm-wave antenna of Itapetinga Radio Observatory (Kaufmann et al. 1982). Concurrent hard X-ray (> 26 keV) measurements were made with the Hard X-ray Burst Spectrometers (HXRBS) on the Solar Maximum Mission (SMM) satellite (Orwig et al. 1980). The X-ray time resolution was 128 ms for the bursts analysed here. Both ground-based and spacecraft measurements had absolute timing accuracy to within a few ms.

At mm-microwaves the degree of circular polarization is derived from the apparent source brightness temperatures of the right- and left-handed polarized components. For the sake of the present analysis we have transformed the temperatures into solar flux units, which are proportional. This does not change the polarization analysis. It is justified by taking into account that the angular

sizes of bursts sources, and also of pre-existing polarized emission sources, are known to be small compared to the 4' half power width of the antenna beam at 22 GHz. We reduced the data using the calibration of the Itapetinga antenna aperture efficiency against known standard radio sources (Venus, Jupiter, Virgo A).

The degree of polarization is derived from the right-handed and left-handed components of flux, S_R and S_L , respectively:

$$p = (S_R - S_L) / (S_R + S_L) \quad (1)$$

The corresponding Stokes parameters are $I = S_R + S_L$ and $V = S_R - S_L$ (i.e., $p = V/I$). It is important to realize that within the beam of single antennas we can have contributions from the burst itself (I_b, V_b) and from the pre-existing active region (I_a, V_a). Both might be the sum of several individual sources

$$I = I_a + I_b = \sum_i (I_a)_i + \sum_j (I_b)_j \quad (2)$$

$$V = V_a + V_b = \sum_i (V_a)_i + \sum_j (V_b)_j \quad (3)$$

and the polarization degree is

$$p = (V_a + V_b) / (I_a + I_b) \quad (4)$$

where both (I_a, V_a) and (I_b, V_b) can also be time variable. In principle, with single-dish data one cannot distinguish between the different contributions. Referring to the excess emission due to the burst alone (I_b, V_b), a relative degree of polarization can be determined

$$p_n = V_b / I_b \quad (5)$$

and the polarization degree can be written as

$$p = \frac{(V_a / I_b) + p_n}{(I_a / I_b) + 1} \quad (6)$$

For bursts which give fluxes which are much more intense than the contribution from the pre-existing active center, we have $I_b \gg I_a$, V_a , and the $p \approx p_r$. This is not the case for the weak events studied in this paper. We have $I_b \lesssim I_a$, V_a , and assuming the net polarization from the pre-existing emission to be weak (i.e., $V_a \approx 0$) we have necessarily $p < p_r$.

3. THE EVENTS ANALYSED

The mm-microwave burst data presented in this section refer to intensities in excess of the pre-existing active region contribution in emission. In order to obtain a better approximation to the polarization degree we will assume that the net polarization from pre-existing emission is weak, i.e., $V_a \approx 0$. The pre-existing contribution in I_a is determined from measurement of the emission of the active center being tracked by the antenna. The following approximate expression is used for the estimate of the polarization degree:

$$p \approx \frac{p_r}{(I_a/I_b) + 1} \quad (7)$$

(a) The event of 14 December 1979, 1406 UT (Figure 1). This event was only recorded at Itapetinga (SMM was not yet launched), but it is an interesting example of a very weak burst compared to the preflare flux level, and displays rapid spikes with high relative right-handed polarization. The Itapetinga antenna was tracking the active region designated by the NOAA number AR 2183 located S15W40. For this burst $S_L \ll S_R$ and is close to the system noise. The time variation of the relative degree of polarization, $p(t)$, corresponds essentially to $S_R(t)$. The relative polarization degree, for the major features labeled 4 and 5 can be larger than 85 percent. The actual polarization degree, according to equation (7), decreases to 8 percent. The time scale for changes in p , as noted in features labeled 1-6, are shorter than 100 ms which implies a rate of change of polarization (dp/dt) of $0.8s^{-1}$ (or 80 percent s^{-1}).

(b) The event of 21 February 1981, 2007 UT (Figures 2,3 and 4). This dense sequence of spikes was not observed in X-rays since the SMM was in satellite night. The Itapetinga antenna was tracking AR2951

located at N12W05. It shows moderate intensity at 22 GHz and moderate relative right-handed polarization (Figure 2). The first two major structures are expanded in Figure 3 and 4, displaying the total flux, $S_R + S_L$, and the time development of the relative degree of polarization $p_r(t)$. There are many polarization changes. Two major changes have maxima leading total flux maxima by 100 ms. The more significant rises in polarization are nearly coincident with rises in flux. The time scales for fast polarization changes range from 50-270 ms. The larger changes in polarization degree (dp/dt), estimated according to equation (7), are of about 4 s^{-1} (or 400 percent s^{-1}).

(c) The event of 26 February, 1981 1227 UT (Figures 5, 6, 7 and 8). This is a sequence of weak complex spikes, right-handed polarized, measured at 22 GHz while tracking AR 2954/5, with the radio maximum located in S26E39. The right-handed output is shown in Figure 5, with the first two time structure expanded in Figures 6 and 7, showing the total flux and the polarization degree time development, $p_r(t)$ at the top. For the first structures (Figure 6) the maxima are coincident with total flux maxima, to within the accuracy of polarization determinations (i.e., 40 ms). Rise phases in $p(t)$ have time scales ranging from 50-120 ms, and are about coincident with rises in $S(t)$. In the second structure (Figure 7), the major structures of the polarization degree attained maxima before total flux maxima by about 230-330 ms. The rise time scales of $p(t)$ are close to 200 ms and appear to precede the rises in $S(t)$. Major-polarization changes estimated accordingly to equation (7), have (dp/dt) of the order of $.2 \text{ s}^{-1}$ (or 200 percent s^{-1}).

In figure 8 we show the simultaneous hard X-ray burst with the major peaks at 22 GHz indicated by the arrows. Within the limits of the timing allowed by the low counting rates ($\sim 100 \text{ ms}$), these peak times are identical.

(d) The event of February 28, 1981 1204 UT. (Figures 9, 10, 11 and 12). This was a simpler sequence of spikes, left-hand polarized. The event

occurred in AR 2958 located at S15E30, that was being tracked by Itapetinga antenna. In figure 9 we show the left-handed output. It was further expanded in figures 10 and 11 for total flux and for polarization degree. The trends are basically the same as observed for the other cases. The major spike (Figure 11) has at least two superimposed structures, and this makes it difficult to associate the $p(t)$ maximum, which leads the major emission peak by about 1 second. For the other three structures (Figure 10) the major polarization maxima preceded major emission maxima by 200-400 ms. The time scales of polarization changes ranged from 100-260 ms. The larger values of (dp/dt) estimated with the use of equation (7) are of the order of 2 s^{-1} (200 percent s^{-1}).

The hard X-ray counterpart is shown in Figure 12. for the lower energy channels (26-52 keV). With the 22 GHz maxima of figures 10 and 11 indicated by arrows. In Figures 10 and 11 we indicate approximate times of the hard X-ray maxima. The major maxima in the degree of polarization appear to lead the maxima in both hard X-ray and 22 GHz emission by 200-1000 msec.

4. POSSIBLE PHYSICAL CAUSES OF FAST POLARIZATION CHANGES

The most remarkable finding encountered in the events analysed here are the fast polarization changes occurring before the associated peaks in microwave and X-ray emission.

Other results can be summarized as follows: (a) sudden changes in circular polarization always correspond to rises in the degree of polarization usually followed by a slower decay; (b) $p(t)$ maxima lead burst emission maxima by $\leq 40 \text{ ms}$ to 1 sec; (c) $p(t)$ rise times are ≤ 40 to 270 msec; (d) the polarization degree in the examples of figures 10 and 11 does not recover to its initial value after each time structure, i.e., there is a suggestion of a permanent change in polarization after every emission time structure; (e) the examples analysed indicate $(dp/dt) = 0.8 - 4 \text{ s}^{-1}$ (80 - 400 percent s^{-1}).

A number of causes can be invoked to explain the observed phenomena and they are briefly discussed here.

(a) Changes in magneto-ionic propagation condition

The sudden variations in $p(t)$ could be attributed to magnetic field variations associated with the primary release of energy. The radiowaves emerging from an optically thin plasma, containing contributions from the active region and from the burst itself, will show a certain circular polarization which is changed by the magnetic field variations. For weak bursts and the onset of larger bursts, the polarization of the emerging radiation may well be controlled by the magneto-ionic conditions. Equations describing polarization degree derived from magneto-ionic theory are given by Ratcliffe (1962). For propagation through and optically thin plasma in the presence of a magnetic field, the following approximation is often used (Kundu 1965):

$$p \approx 2Y_L / (1 + Y_L^2) \quad (8)$$

where the magneto-ionic parameter $Y_L = (f_H/f) \cos \varphi$, $f_H = 2.8 \times 10^6 H$ (Hz) is the gyrofrequency, H is the magnetic field in gauss, φ is the angle between the line of sight and the lines of force, and f is the observing frequency in Hz. In practice the approximation is used for a wide range of φ (i.e., $\pm 70^\circ$). At high frequencies (such as $f = 22$ GHz) and for fields smaller than about 10^3 gauss, $f \gg f_H$, $Y_L^2 \ll 1$ and equation (6) becomes

$$p \approx 2Y_L \quad (9)$$

The additional effect on polarization due to gyroabsorptive layers (Zheleznyakov, 1970; Kaufmann and Santos, 1974; Steffen, 1975) can be entirely neglected for the 2nd and 3rd harmonic.

The medium acts as a polarizer for all emerging radiation components. In this first assumption, and especially at the onset of

small bursts or spikes, the contribution from the intrinsic polarization of the burst sources is considered small. Any changes in the field or in its angle with respect to the observer will produce variations in the polarizing medium and, thus, in the degree of polarization of the emerging radiation. Differentiating equation (9) and substituting for Y_L we obtain

$$\frac{dp}{dt} = \frac{5.6 \times 10^6}{f} \left(\cos \varphi \frac{dH}{dt} - H \sin \varphi \frac{d\varphi}{dt} \right) \quad (10)$$

The observed rapid increase in $p(t)$ could be associated with the primary transient itself. The major changes in polarization are observed to precede to the maxima emission in mm-microwaves and hard X-rays. The changes could be caused . . . either by changes in H or in φ , or both combined.

(b) Intrinsic polarization of the burst sources

The polarization degree intrinsic to the gyrosynchrotron sources of the microwave bursts can be important, and time variable. The importance of the circular component of polarization will depend on the energy of the electrons involved. Dulk and Marsh (1981) have developed simplified equations for mildly-relativistic non-thermal and thermal electron distributions.

For non-thermal electrons with isotropic pitch angle distributions and power law spectra ($n(E) = KE^{-\delta}$) the degree of circular polarization in optically thin conditions is expressed in terms of the power-law exponent, δ , and the angle φ between the direction of the magnetic fields lines and the line of sight

$$p \approx k_1 \cdot 10^{k_2 \delta} \cdot 10^{k_3 \cos \varphi - k_4 \cos^2 \varphi} \left(\frac{f}{f_H} \right)^{-k_5 - k_6 \sin \varphi} \quad (11)$$

where k_{1-6} are constants (Dulk and Marsh 1981). Quantitatively, the

highest degree of polarization can be attained for small values of φ , adopting $2 \leq \delta \leq 7$. If this were the case for the observed polarization changes then the microwave source should be at the footpoints of the magnetic loops rather than at the top of these loops i.e., for sources not too far from the solar central meridian, and assuming a simple magnetic loop geometry. Sudden increases in polarization might simply reflect fast changes either in δ , φ or H .

The simplified expression derived for polarization degree of thermal electrons, in optically thin conditions, with emitting electrons having an isotropic pitch angle distribution and a Maxwellian energy distribution depend on the electron temperature T :

$$p \approx q_1 T^{-q_2} \cdot 10^{q_3 \cos \varphi - q_4 \cos^2 \varphi} \left(\frac{f}{f_H} \right)^{q_5 - q_6 \sin \varphi} \quad (11)$$

where q_{1-6} are constants (Dulk and Marsh, 1981). Again the higher polarizations degree are obtained for small angles φ , i.e., with the emitting sources closer to the magnetic footpoints. Fast polarization changes could imply sudden changes in T , φ or H .

In both the thermal and non-thermal case, there are no apparent reason why the polarization degree should peak before the microwave and hard X-ray emission. A suggestion has been given by Brown (1982) after which one could conceive the isotronisation of the electron distribution by magnetic wave scattering on a time scale shorter than that of collisional effects. This interesting possibility would explain qualitatively why the polarization changes quickly before the intensity peaks.

For both the thermal and the non-thermal cases, however, we can get fast changes in p by changes in the magnetic field, i.e., a variation of (f/f_H) . If this is the case, with the sources located in the direction of the footpoints, the effect might be combined (and nearly time coincident) with the changes in magneto-ionic propagation conditions for emerging mm-microwave radiation, as suggested in the first assumption. The fast polarization changes peaking before the intensity might be explained

similarly as a combination of the causes which, in this case, would have the same origin.

(c) Spatial and time variation of polarized sources in single antenna beam

As it has been briefly reviewed in the Introduction, interferometric observations of microwave bursts have indicated that within a single antenna beam we may have various sources oppositely polarized, moving in space and changing in intensity and polarization degree.

In a simplified situation we could assume that the electrons initially are accelerated from the top into the legs of an asymmetric magnetic arch (e.g., Kundu and Vlahos 1979). The polarization degree would dominate in the sense of the magnetic arch leg which has the stronger magnetic field. The time development of polarization would then depend on the relative importance of the combined polarized emission sources, with different senses in the two legs of the loop within the same antenna beam. The time of maximum emission would depend on the growth times of the emission mechanisms, and would be independent of polarization vs. time net effects. The lack of time coincidence of polarization peaks and emission peaks, could be explained in this way. This explanation, however, wouldn't require that the peak of polarization should always precede the peaks in emission at mm-microwaves and hard X-rays, as suggested in the examples analysed in this paper.

The interferometric observations of microwave bursts also indicate that the major source at the top of a loop elongates towards the footpoints direction, eventually showing oppositely polarized regions at the ends (Marsh and Hurford, 1980; Kundu, 1981). This effect, however, is known to happen in a time scale of tens of seconds, which is

considerably larger than the time scales of the fast polarization changes studied here (10^{-2} - 10^{-1} sec). The superimposed spikes seem to correspond to sources at different locations, and spatially unresolved to 1 arcsec (Hurford et al., 1979, 1982). For the present explanation each 22 GHz spikes should then consist of at least two oppositely polarized emitting sources to account for the observed fast $p(t)$ effects. They should be located close to the loop footpoints in order to show polarized emission i.e., for a typical foot points separation of 10^9 cm, the two spike sources would be spatially separated by about 13 arcsec, which is considerably larger than the suggested size for the region over which the spikes sources are located (Hurford et al., 1979; 1982; Kundu et al., 1982b).

The detection of hard X-ray spikes from the footpoints of magnetic arches was recently reported by Hoyng et al. (1981). The X-ray emission was attributed to beams of accelerated electrons. These beams could also produce mm-microwaves in non-thermal models, on a sufficiently fast time scale to account for net polarization effects due to spatial time variation of polarized sources. However, the larger time delays observed between hard X-ray and microwave emission (Kaufmann et al., 1982b) do not favour the non-thermal models, in which all emissions are closely synchronized unless a microwave propagation effect is involved due to high source density.

The composite effect of time varying polarized sources moving within the antenna beam might well account for the known slower changes of polarization degree with time, on time scales of several seconds to minutes, discussed in Section 1 (Introduction). Sensitive interferometer microwave observations, with a time resolution < 100 ms, are required to understand the temporal and spatial variation of polarized sources in solar bursts.

5. FAST POLARIZATION CHANGES AND PRIMARY MAGNETIC TRANSIENTS

The observed time scales of the fast changes in $p(t)$ at

mm-microwaves can be thought to be closely related to time scales of the primary magnetic transients, which are believed to initiate the burst phenomena.

Cal Discussion of fast changes in magnetoionic conditions. Assuming that changes in the magnetoionic propagation conditions for all emerging mm-microwaves are dominant, at least for bursts small compared to pre-burst flux levels, or for the onset of larger bursts, expression (10) can be further discussed. The signs in (10) depend on polarization senses and on whether there are increases or decreases in H , ψ . For the sake of this discussion we will use absolute values. The fast polarization changes could be attributed to either $|dH/dt|$ or $|d\psi/dt|$, or a combination of both.

Let us assume that the radiation emerges from a magnetic tube, with length $L \approx 10^9$ cm, cross-section $A \approx 10^{16}$ cm², magnetic field $H \approx 500$ gauss, and a reference angle $\psi \approx 45^\circ$ between the field lines and the line of sight. The magnetic flux will be $\Phi = A.H = 5 \times 10^{18}$ Maxwells.

If the observed $|dp/dt| \approx 1 \text{ s}^{-1}$ is due primarily to $|dH/dt|$ in equation (10) (with $|d\psi/dt| \approx 0$), we obtain $|dH/dt| \approx 5.5 \times 10^3 \text{ gauss s}^{-1}$. In a time scale of 100 ms, this means a change in equivalent magnetic field of 550 gauss - which is unrealistically high. A plausible field variation of, say, 10 percent (i.e. ~ 50 gauss) would imply a time scale of 9 ms, which is much smaller than the 40 ms timing accuracy of the data used in this study.

The energy release rate ($\Delta W/\Delta t$) can be related to the magnetic field change rate (dH/dt), assuming the radio and X-ray sources are the sites of magnetic dissipation (Brown 1982). In a constant volume, V , we have

$$V \frac{d}{dt} \left(\frac{H^2}{8\pi} \right) = \frac{\Delta W}{\Delta t} \quad (12)$$

and thus

$$V = 4\pi \frac{(\Delta W / \Delta t)}{H (dH/dt)} \quad (13)$$

If we assume the thick-target energy release rate required for hard X-ray production of about 10^{28} erg s^{-1} (Spicer 1977; Brown and Smith 1980; Kahler et al. 1980) and with $|dH/dt| \approx 5.5 \times 10^3$ s $^{-1}$ from the microwave data then for $H \approx 500$ gauss, we obtain a volume $V \approx 4.6 \times 10^{22}$ cm 3 , and a scale size for the dissipation region of $L \approx 3.6 \times 10^7$ cm (360 km), which is very plausible (Alissandrakis and Kundu 1978; Brown et al. 1979; Hurford et al. 1979, 1982).

Alternatively we might associate the observed fast changes in polarization to a rapid change of the angle through which the field lines are observed. A magnetic flux tube can gain "free magnetic energy" by being twisted by a certain angle $\Delta\chi$. The energy liberation might imply in a sudden untwisting, which we can compare to $|\Delta\psi|$ in equation (10). The free magnetic energy stored is, after Sturrock and Uchida (1981):

$$\Delta W = \frac{\Phi^2 (\Delta\chi)^2}{16\pi^2 L} \quad \text{erg} \quad (14)$$

Using the same flux tube parameters as before, with $|dp/dt| \approx 1$ s $^{-1}$, in 100 ms, assuming now $|dH/dt| = 0$ in equation (10), we obtain $\Delta\psi \approx 1$ rd. Comparing $\Delta\psi \equiv \Delta\chi$, we get

$$\Delta W \approx 1.6 \times 10^{26} \text{ erg} \quad (15)$$

which is a very reasonable value for the energy content of a very small burst (Brown and Smith 1980; Kahler et al. 1980).

b1 Time scales and energy release rates. The observed effects in $p(t)$ appear to be associated with each flux time structure, which might be representations of elementary burst processes (Frost 1969; van Beek et al. 1974). We can attribute an energy content of 10^{27} erg to a very small burst (Brown and Smith 1980; Kahler et al. 1980), released in less than about 100 msec, and obtain an energy release rate $dW/dt = 10^{28}$ erg s^{-1} . This energy release rate has the same order of magnitude as rates inferred for larger bursts, with total time durations of $10^2 - 10^3$ seconds (Spicer 1977; Brown and Smith 1980, Kahler et al. 1980). The present results suggest that either small or large events can be a response to primary processes having the same order of magnitude for the energy release rate.

The above suggestion on comparable energy release rates for larger and smaller bursts might rule out primary mechanisms based on burst sources with continuous energy release for a time comparable to the total burst duration. Instead, one should assume a number of discrete elementary processes piling up throughout the event duration, as has been suggested semi-empirically (Kaufmann et al. 1978) and independently by model prediction (Brown et al. 1980). Indeed, the recently available high time resolution burst data are showing that fast time structures are quite common at hard X-rays (Dennis et al. 1981; Orwig et al. 1981). At mm-waves (Kaufmann et al. 1980), mean fluxes were found to be proportional to repetition rates of superimposed fast time structures, suggesting a quasi-quantization in energy.

Finally, as for primary energy release mechanisms, the release rates of the order of 10^{28} erg s^{-1} are several orders of magnitude higher than predictions of various models based on Petschek's (1963) mechanism of magnetic field lines merging in long diffusion regions with extremely thin neutral sheets. These problems were reviewed by Smith (1979), Brown and Smith (1980) and Kahler et al., (1980). Multiple tearing mode processes in magnetic islands occurring in supertwisted antiparallel field configurations seem more attractive to reconcile with the present results (Kuperus 1976; Samain 1976; Spicer 1977). Spicer (1977, 1981) has reviewed a variety of possible

primary releases, in different geometries, presenting energy release rates, time scales and multiplicities adequate for further discussion of the events analysed here. Explosions of magnetic islands in volumes as small as 10^{20} cm^3 , initial plasma conditions with density 10^{12} cm^{-3} , temperature $5 \times 10^5 \text{ K}$, poloidal field component of 500 gauss, could provide energy release rates of $4 \times 10^{27} \text{ erg s}^{-1}$ (Spicer 1977).

6. CONCLUSION

We report the discovery of well defined sudden fast changes in the degree of circular polarization attaining maximum prior to small spikes in mm-microwave emission in multiply-spiked bursts. This discovery required high sensitivity observations with a time resolution of $\leq 50 \text{ ms}$. At least for one event, the transients also precede similar hard X-ray emission maxima.

The discussion of possible causes for the fast polarization effects indicate that sudden perturbation of the prevailing magnetic field, which regulates the polarization of pre-existing sources, and part of the intrinsic polarization of burst sources, might be the simplest and dominant agent, particularly for bursts weak in comparison to the contribution of the pre-existing active center. For intense bursts, the intrinsic polarization effects should dominate and, due to their complexity, the polarization of various sources combined within the antenna beam may become significant. Some large bursts, observed simultaneously by Itapetinga and SMM are currently being analysed, and results will be published in the near future.

The time scales of the fast mm-microwave polarization changes can be associated with time scales of primary magnetic transients. Energy release rates of weak, or elementary burst spikes, are suggested to be comparable to rates usually attributed to great bursts. As a consequence, large bursts could be conceived as composed of a large number of elementary discrete events, which would not be necessarily resolved in time by currently existing instrumentation.

For more intense bursts, the accuracy of the polarization determination can be improved considerably. The "noise" in $p = V/I$, equation (1) reduces as I increases. Hence, it should be possible to extend these measurements down towards the 1 ms time resolution of the mm-microwave observations, themselves, for the largest bursts.

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FIGURES CAPTIONS

Fig. 1 - A sequence of rapid very small spikes recorded on 14 Dec. 1979, showing very high relative circular polarization degree (i.e., relative to pre-existent flux level). The pre-burst emission level of 5 s.f.u. was subtracted from the total flux in this time interval. The data in the small box are expanded in the top of the figure. The spikes show significant fluctuations in times shorter than 100 msec. Vertical scales are in solar flux units.

Fig. 2 - The right-handed polarization output of a multi-structured burst obtained at 22 GHz on 21 Feb. 1981. Intensity scale is in solar flux units. The vertical lines indicate the two time intervals shown expanded in Figures 3 and 4. The pre-burst emission level of 4s.f.u. was used for polarization determination, accordingly to equation (7).

Fig. 3 - Time expanded section of the first time interval for the burst shown in Fig. 2. Time at the start of the plot corresponds to 20^h 07^m 20^s.22 UT. Total flux $(S_R + S_L)/2$ is represented in solar flux units. Relative polarization degree p_r is at the top, derived from 40 ms averages of right- and left- handed outputs. Time differences are indicated between corresponding peaks in flux and degree of polarization. Time scales for changes in the relative degree of polarization are also indicated. Error bars indicate estimated inaccuracies in the determination of the degree of polarization.

Fig. 4 - Time expanded section of the second time interval for the burst shown in Fig. 2 plotted similarly to Fig. 3. Time at the start of the plot corresponds to 20^h 07^m 22^s.42 UT. Flux is in solar flux units.

Fig. 5 - Another sequence of 22 GHz small spikes right-handed polarized recorded on 26 Feb. 1981. The pre-burst emission level of about 2 s.f.u. was used for polarization estimates according to equation (7). Vertical lines indicate the two time intervals which are shown on an expanded time scale in Figure 6 and 7. Flux is in solar flux units.

Fig. 6 - Time expansion of total flux and relative degree of polarization (p_r) for the first in time interval shown in Fig. 5 plotted similarly to Fig. 3. Time at the start of this plot corresponds to $12^h 27^m 29^s.80$ UT. The arrow shows the time of the first maximum observed in hard X-rays (see Fig. 8). Flux is in solar flux units.

Fig. 7 - Time expanded section of the second time interval for the burst shown in Figure 5, plotted similarly to Fig. 3. Time at the start of the plot correspond to $12^h 27^m 35^s.20$ UT. Flux is in solar flux units. The arrow shows the time of the second maximum observed in hard X-rays (see Fig. 8).

Fig. 8 - Hard X-ray burst recorded by the HXRBS experiment on board the SMM satellite in coincidence with the 22 GHz burst shown in Figure 5. The observed rate of events in the energy range from 28 to 55 keV is plotted with one point every 128 ms. The error bars correspond to ± 1 standard deviation statistical uncertainties calculated as the square root of the number of counts observed during each 128 ms interval. The arrows indicate the times of the first 22 GHz emission maximum in Fig. 6 and the two maxima in Fig. 7.

Fig. 9 - A simpler sequence of left-handed spikes obtained at 22 GHz on 28 Feb. 1981. Vertical lines shows the two time interval plotted on an expanded time scale in Figures 10 and 11. The pre-burst emission level of about 8 s.f.u. was used in equation (7) for polarization estimation. Flux is in solar flux units.

Fig. 10 - Time expansion of total flux and relative degree of polarization (p_r) for the first time interval of the 22 GHz burst shown in Fig. 9 plotted similarly to Fig. 3. Time at the start of the plot correspond to $12^h 04^m 33^s.42$ UT. The arrows indicate the time of the corresponding maxima in hard X-rays (see Fig. 12). Flux is in solar flux units.

Fig. 11 - Time expansion of total flux and relative degree of polarization (p_r) of the second time interval of the 22 GHz burst shown in Fig. 9. plotted similarly to Fig. 3. Time at the start of the plot correspond to

12^h 04^m 41^s.00 UT. Flux is in solar flux units. The arrow indicate the time of the major maximum in hard X-rays (see Fig. 12).

Fig. 12 - Hard X-ray burst recorded by the HXRBS on SMM in coincidence with the 22 GHz burst on 28 Feb. 1981 shown in Fig. 9 plotted similarly to Fig. 8.

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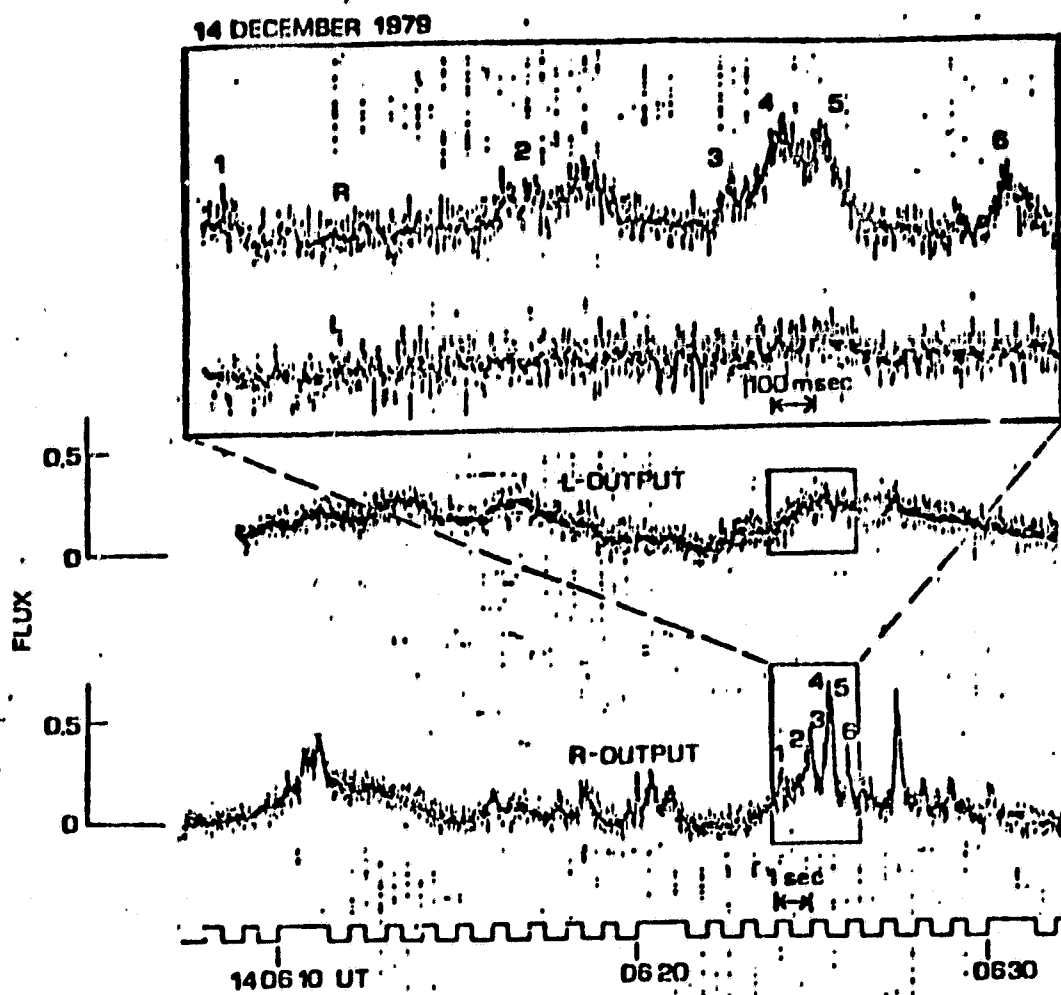


Fig.1

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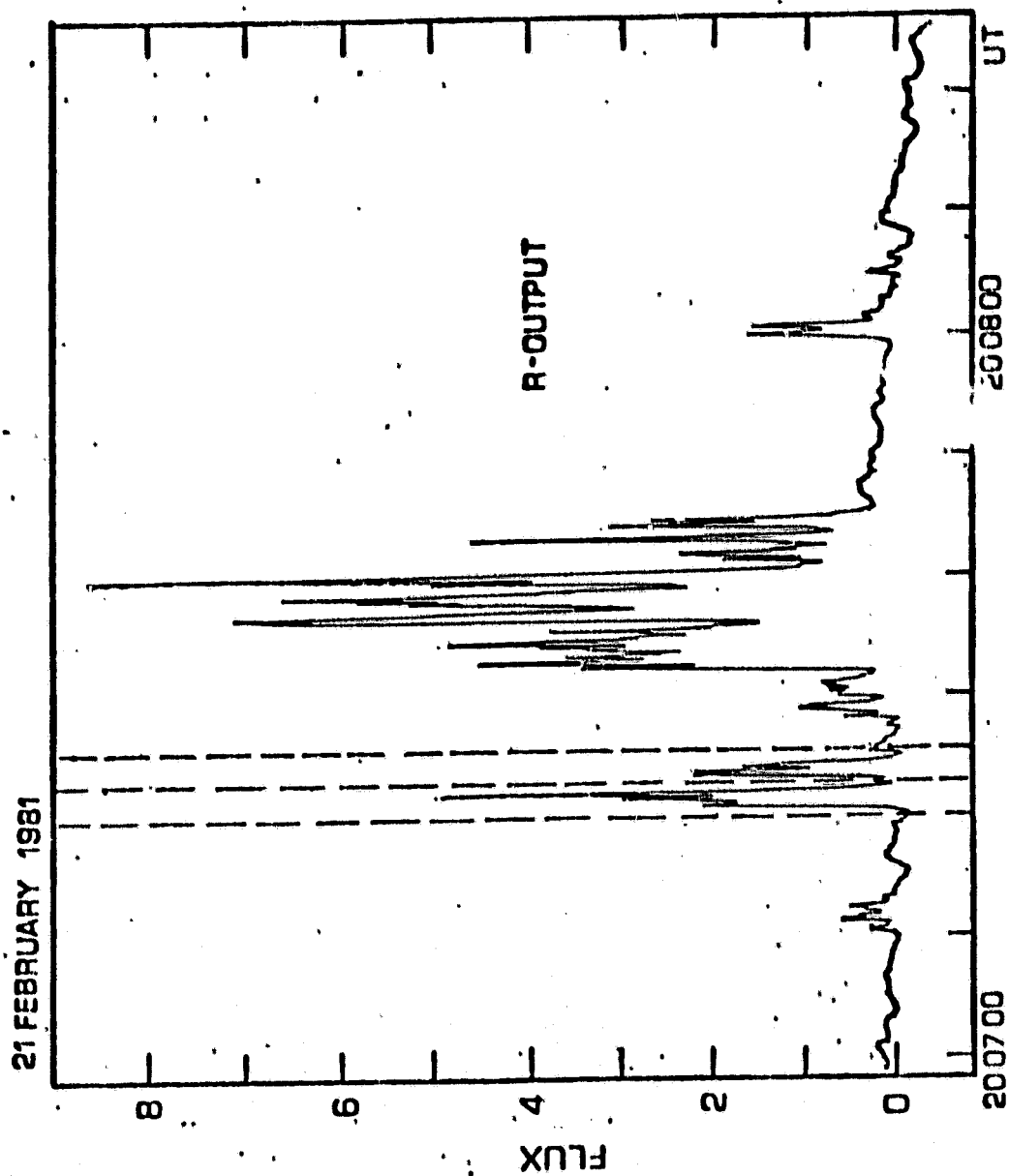


Fig. 2

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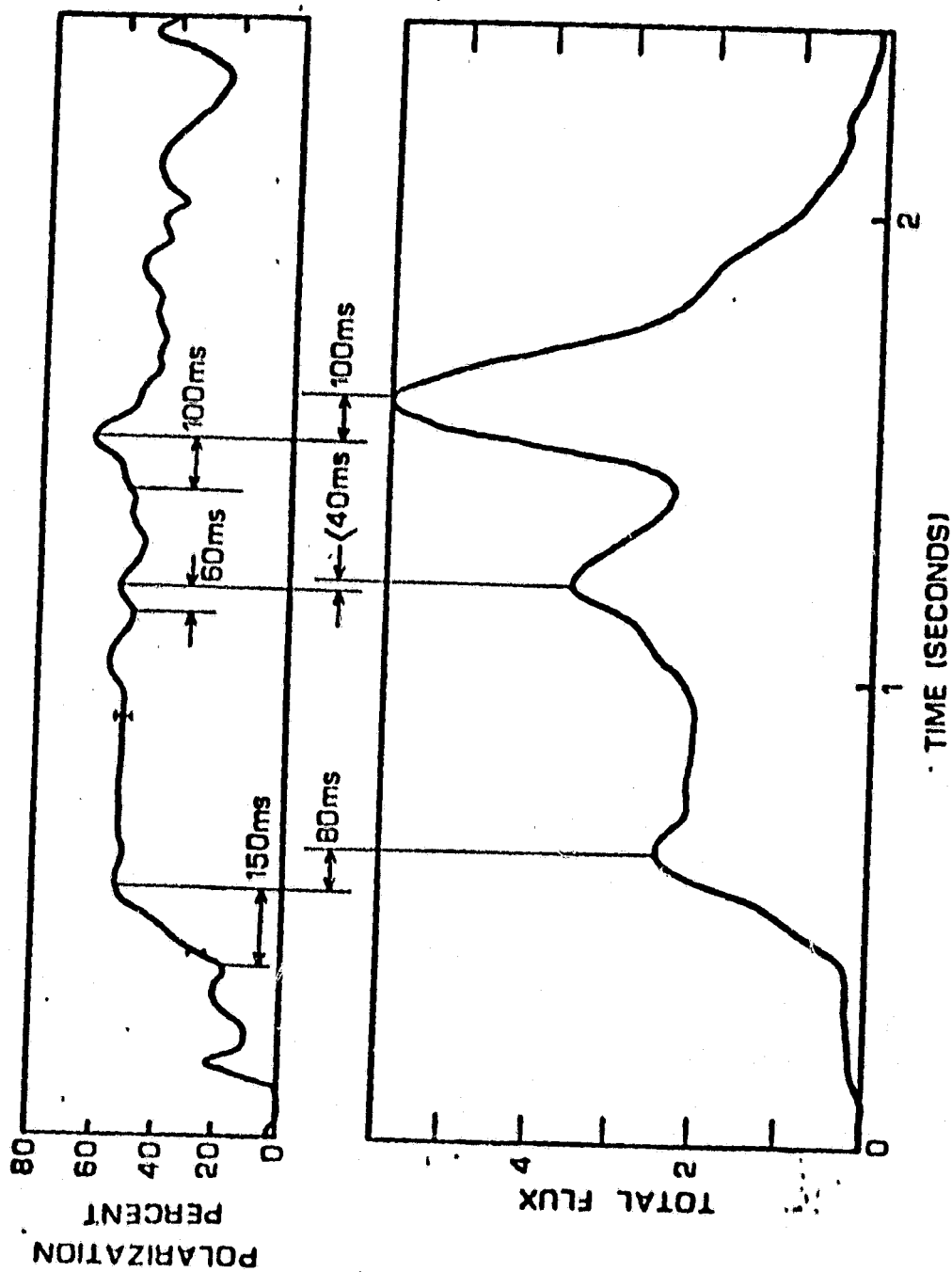


Fig. 3

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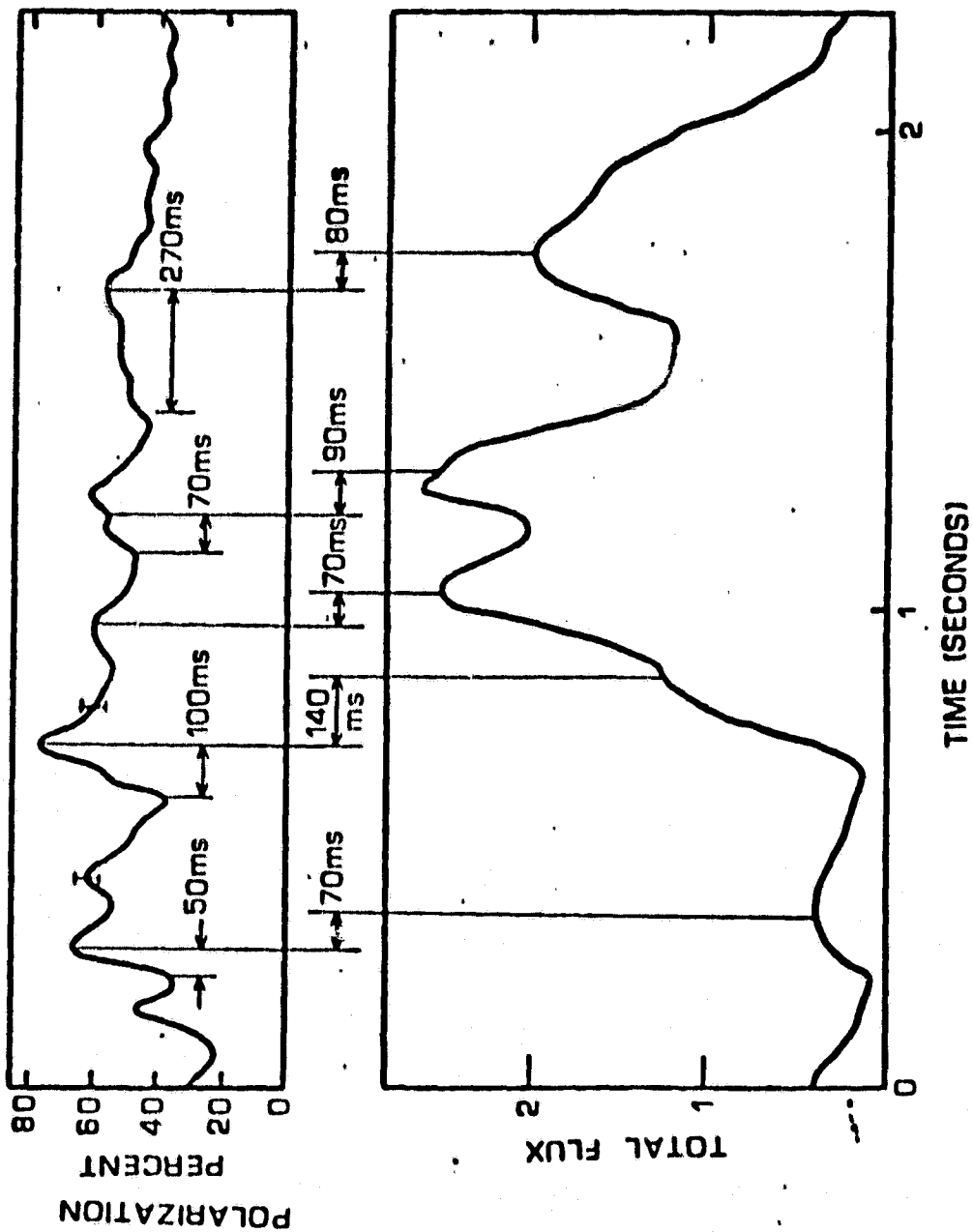


Fig. 4

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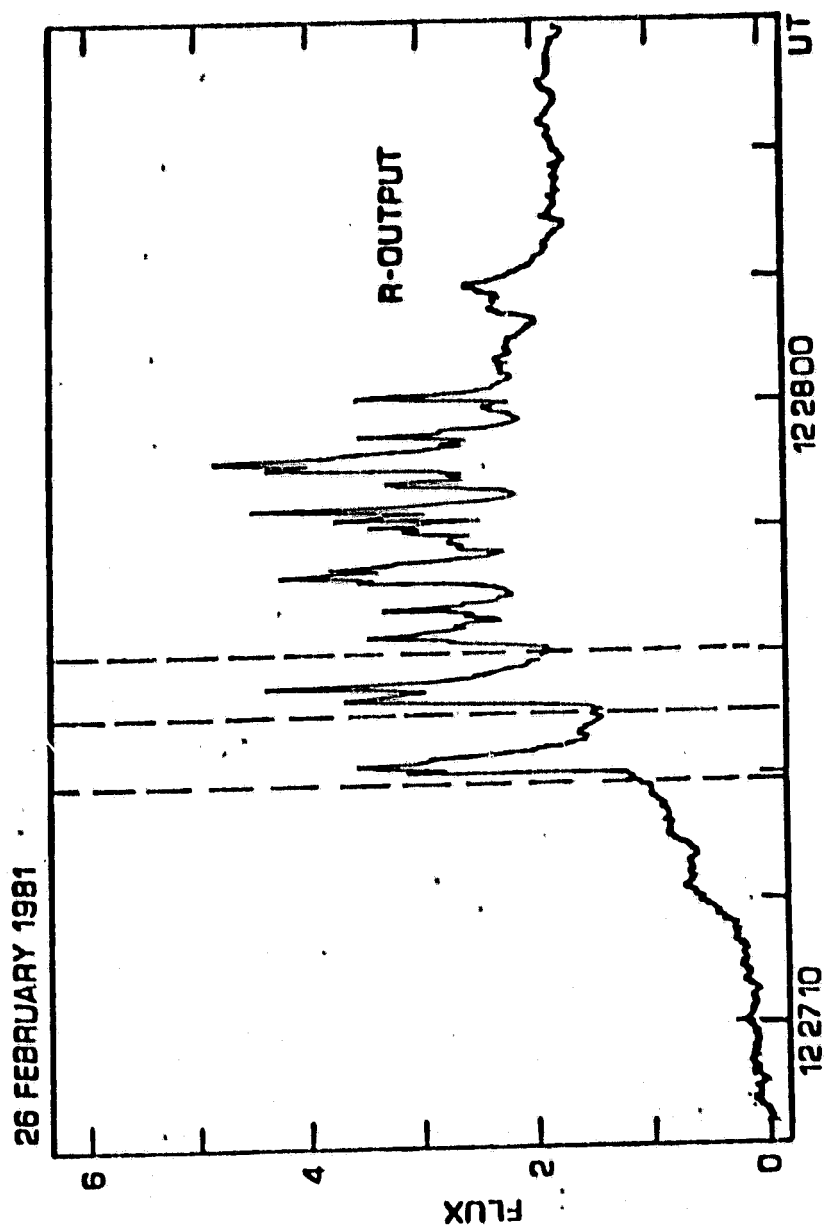


Fig. 5

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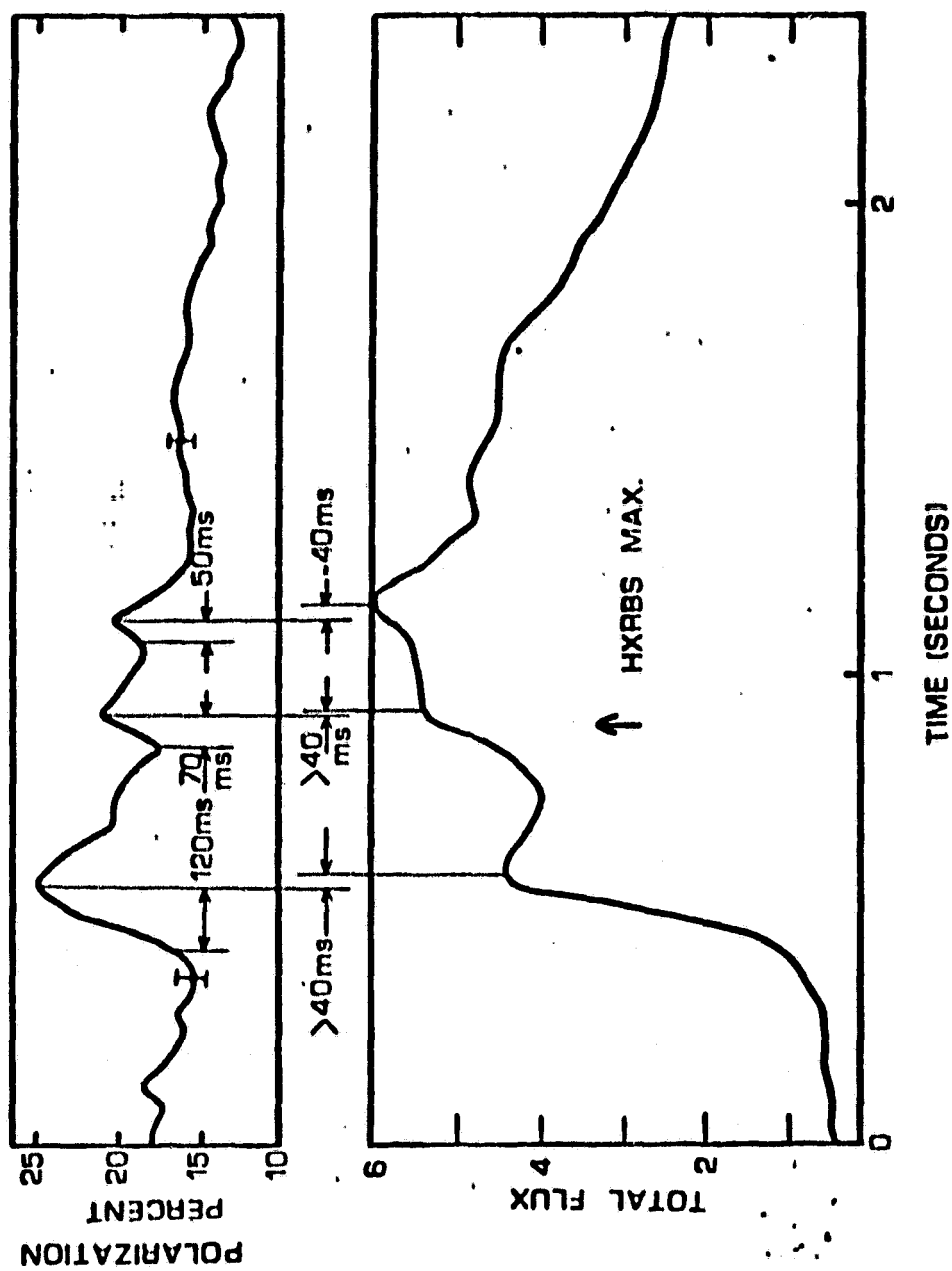


Fig. 6

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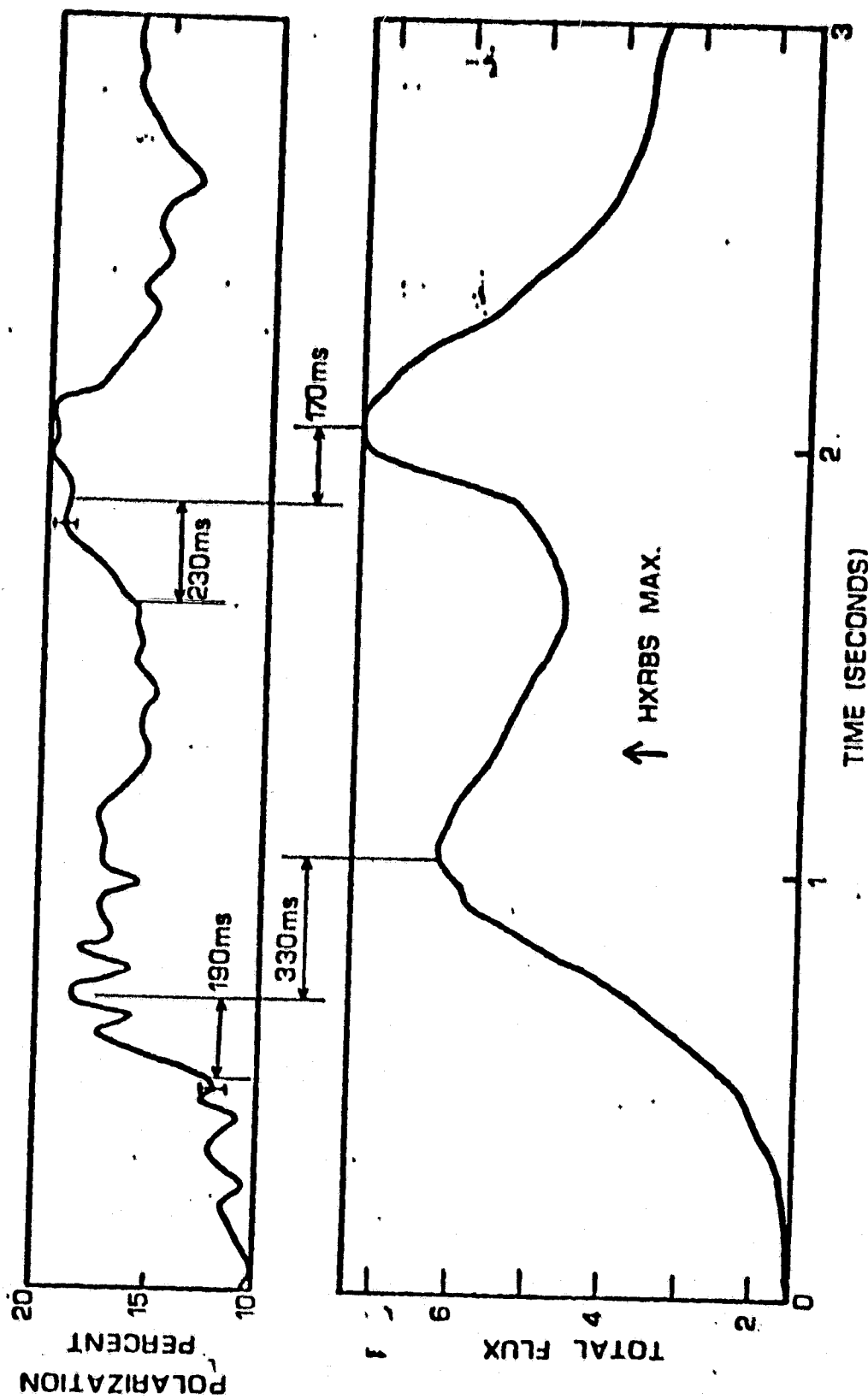


Fig. 7

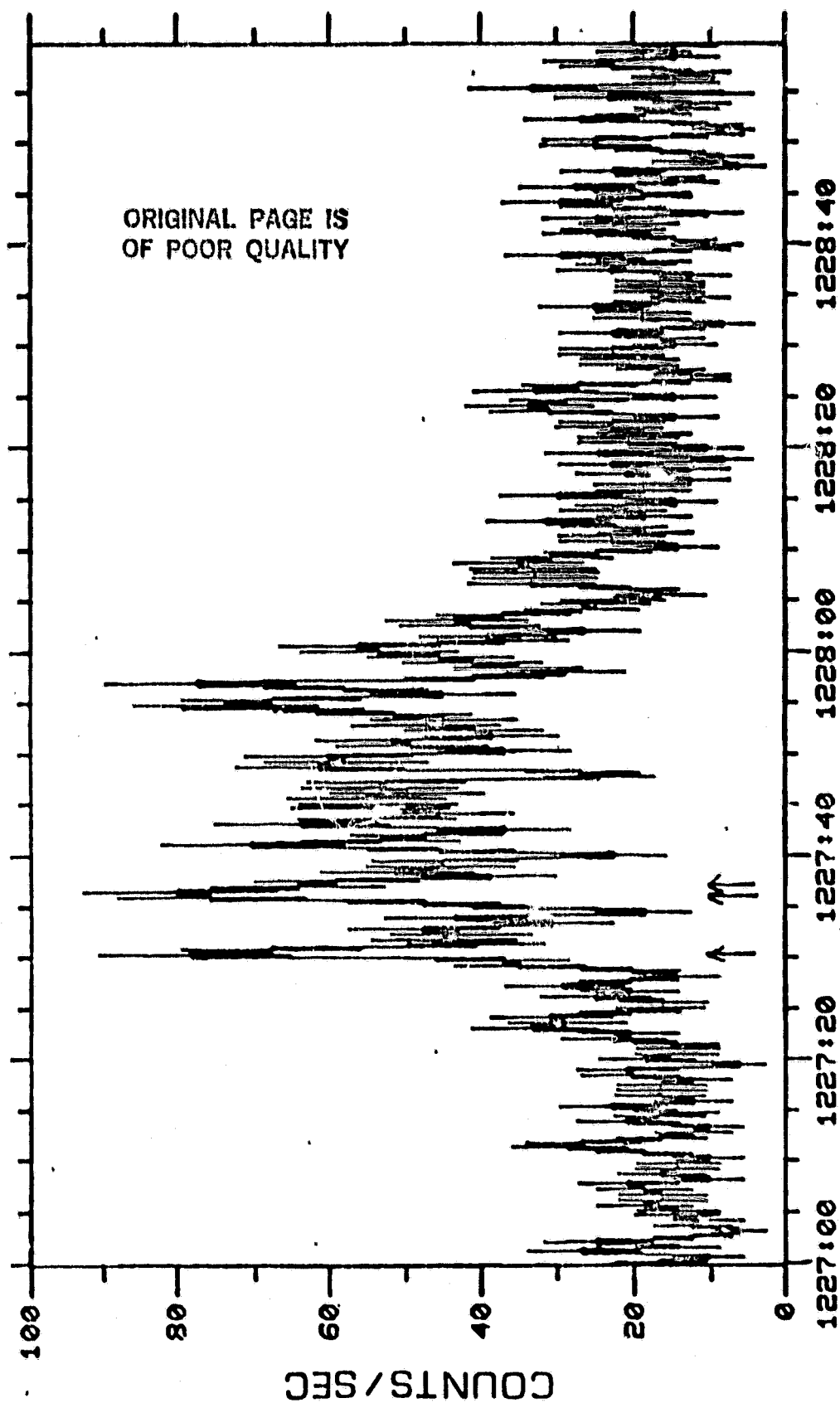


Fig. 8

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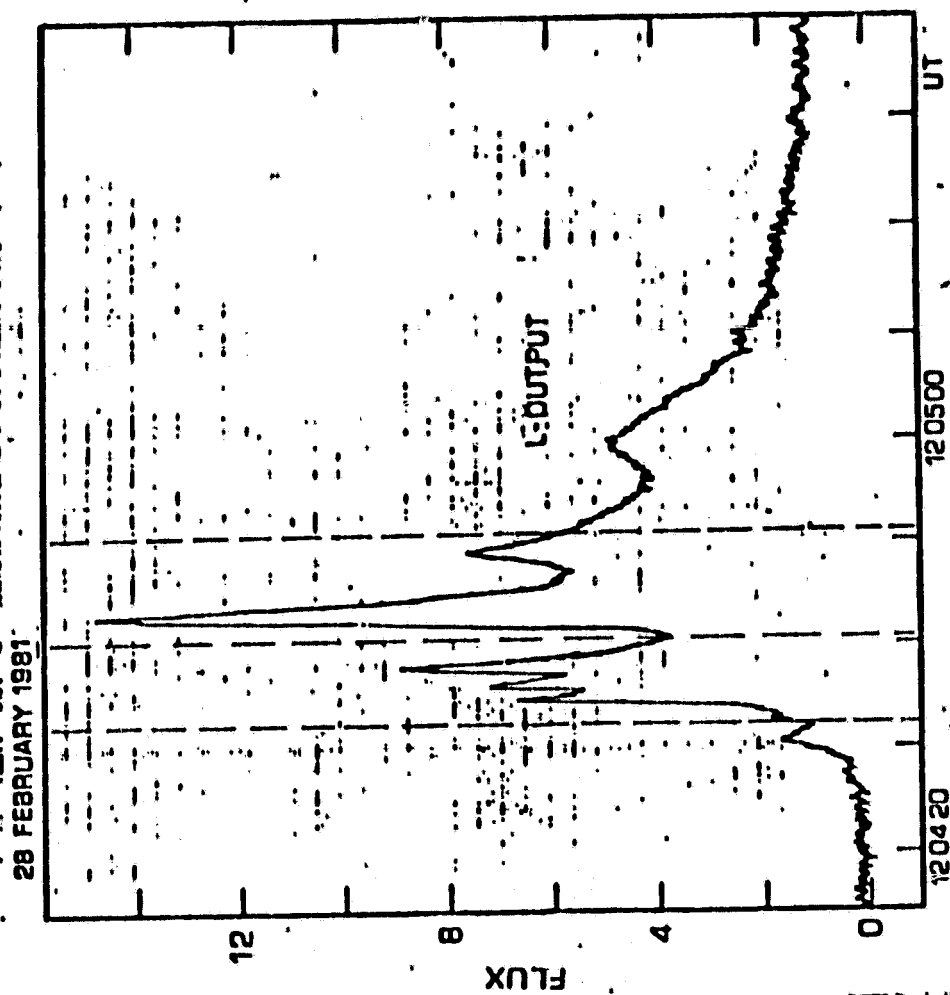


Fig. 9

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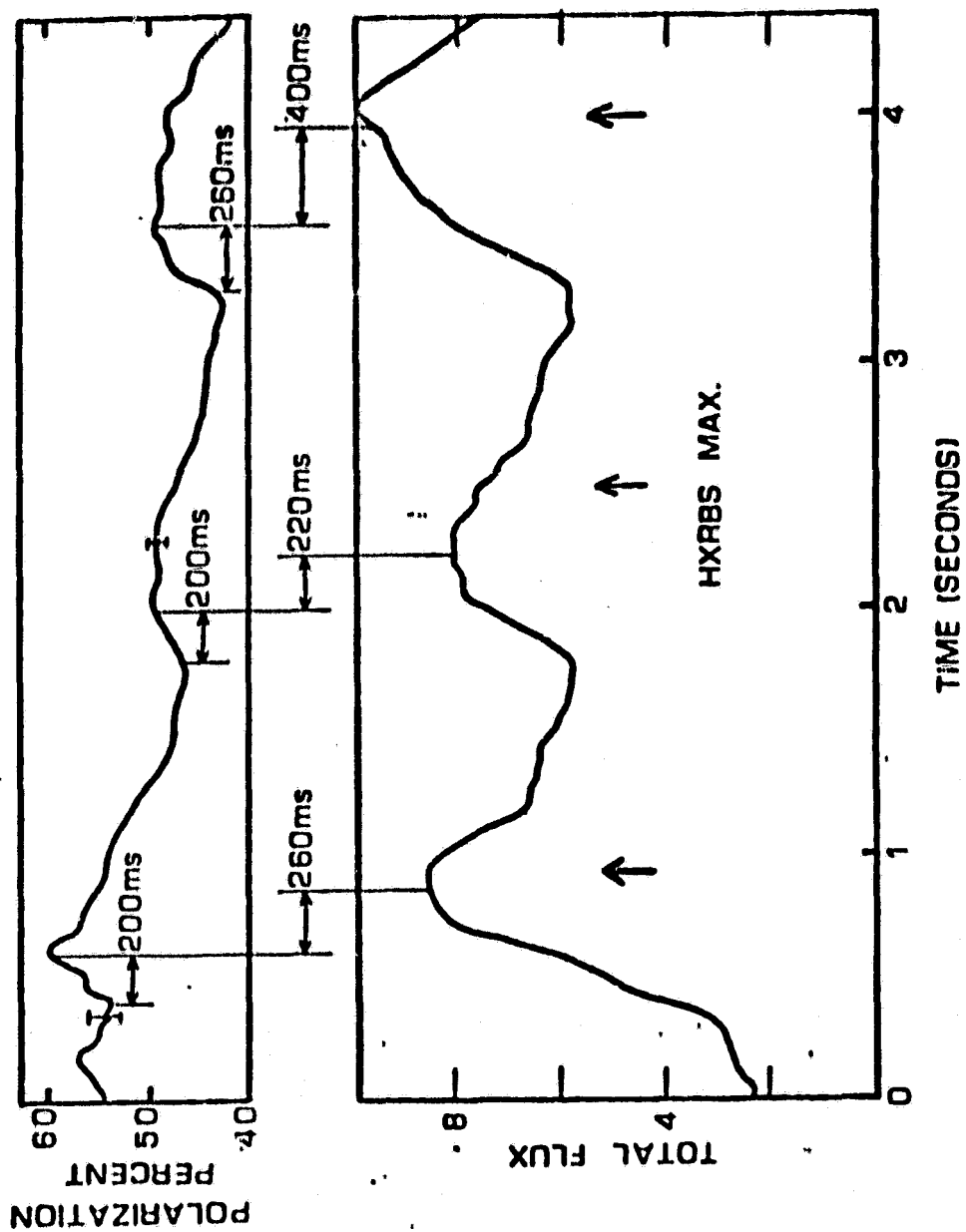


Fig. 10

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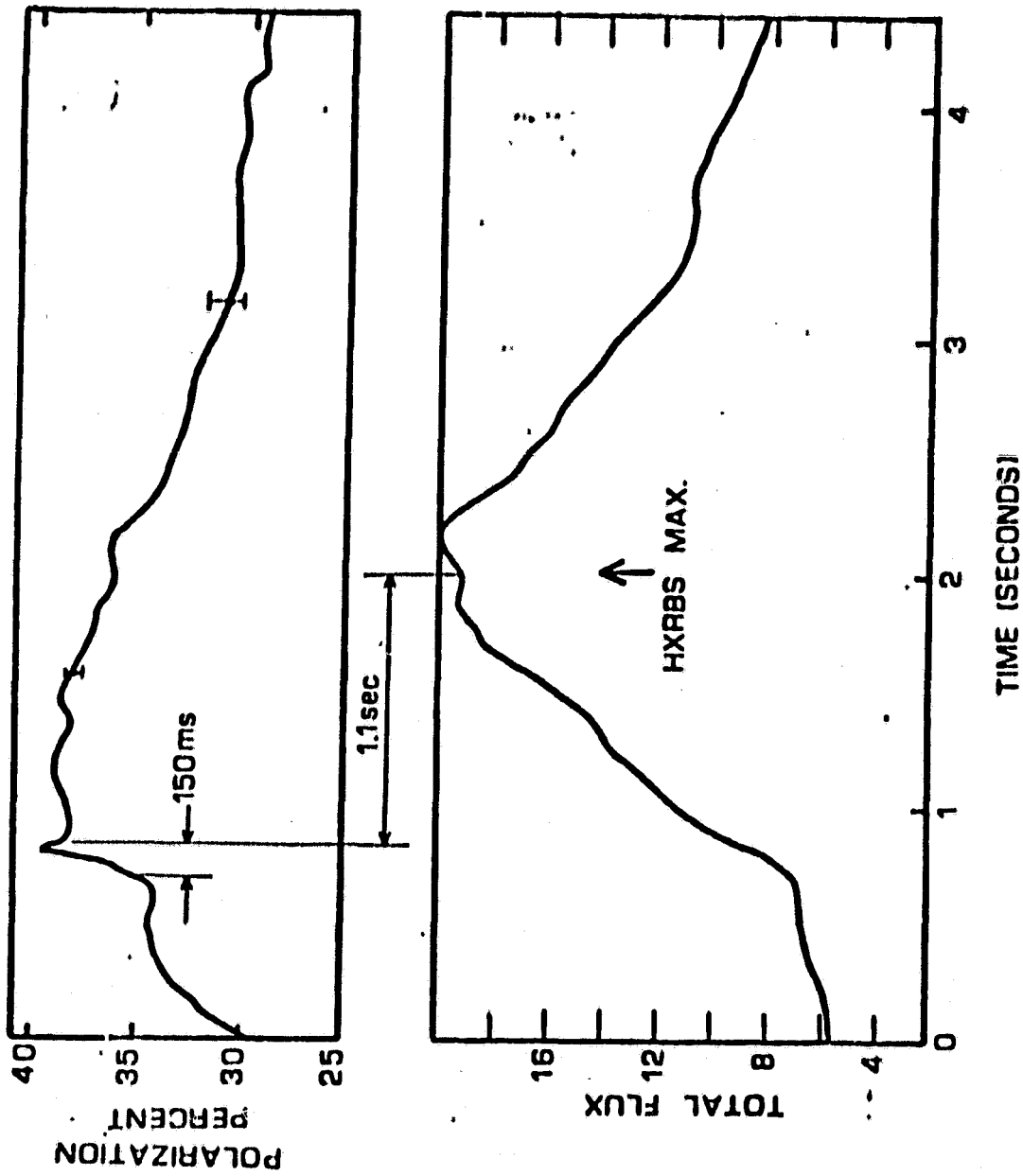


Fig. 11

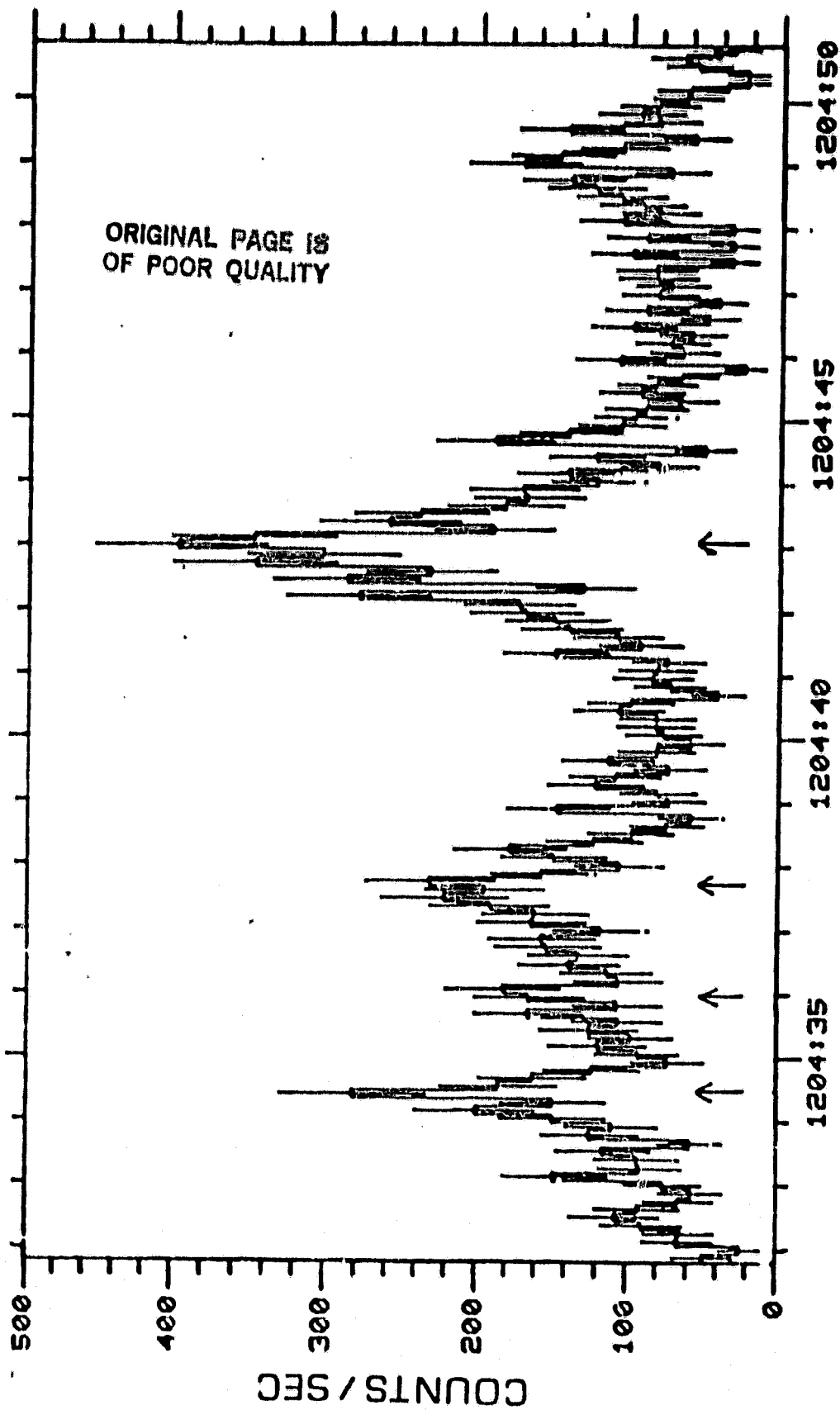


Fig. 12